The potential use of heather, *Calluna vulgaris*, as a bioenergy crop

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Abstract

Calluna vulgaris can and does grow in areas considered unsuitable for production of biomass crops. In the UK, *Calluna* vegetation is regularly controlled by burn management and if instead the lost biomass could be harvested would it represent a viable energy crop? This study used established techniques for other energy crops to assess the energy yield, energy efficiency and the greenhouse gas savings represented by cropping of *Calluna* under two scenarios; only harvested on the area currently under burn management; and harvested on the present total area of *Calluna* in the UK. The study can consider biomass potential across the UK and can include altitude changes. The study can show that *Calluna* would represent an efficient energy crop in areas where it would not be possible to revert to functioning peat bogs. The energy efficiency was 65 ±19 $GJ_{output}\ GJ_{input}^{-1}$ with GHG savings of up to 11 tonnes $CO_{2eq}ha^{-1}yr^{-1}$. When considered across the UK the potential energy production was up to 40.7 $PJyr^{-1}$ and the potential greenhouse gas saving was upto -2061 ktonnes $CO_{2eq}yr^{-1}$ if the all *Calluna* could be brought into production and substituted for coal.

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1. Introduction

The UK government has committed to increasing the use of biomass for energy as part of its commitment to European Commissions 20:20:20 policy [1,2]. The UK Biomass Strategy estimates that the UK has the potential for 278 PJ yr^{-1} energy production from biomass equivalent to about 15 Mtonnes of dry biomass. The UK Biomass Strategy suggests that 22% of this target will be met from the production of ligno-cellulose crops and that equates to about 3500 km^2 of land given over to production at rates equivalent to 9 tonnes of dry biomass ha^{-1}. Most of this commitment will be met by the development of short rotation coppice (SRC) and growing of *Miscanthus spp*. There are limitations on the development of these crops not least of which is that they may need to be planted on ground which has other productive uses. Bauen et al. [3] when plotting the spatially suitability of UK land for *Miscanthus* production showed that the UK uplands were unsuitable for any energy crop production. However, heather, *Calluna vulgaris* will readily grow in the UK upland regions.

There are several reasons why *Calluna vulgaris* (henceforward referred to as *Calluna*) could represent an excellent biomass crop. Firstly, the burning of *Calluna* vegetation is a typical management strategy in the UK [4] and so available energy is already being lost. Second, the burning is conducted for a number of reasons to enhance the productivity of the environment. *Calluna* goes through a life cycle from pioneer through building to mature and finally degenerate [5]. Late stage mature and degenerate *Calluna* will blanket an environment which creates an unproductive ecosystem because *Calluna* is not a preference food for grazers [6]; and it is poor forage for red grouse (*Lagopus lagopus*). Furthermore when it becomes dominant it lowers the biodiversity [7] and represents a large fuel store prone to wildfire [8]. Therefore, managed burning has been used primarily to break up stands of *Calluna* and by providing stands of mixed age to improve grazing (largely for sheep) and to provide shelter for nesting grouse in the old stands of *Calluna* next to young *Calluna* for forage. Managed burning has then had the added value of helping control wildfires by lowering fuel loads and providing fire breaks. Therefore, if burning of vegetation is occurring anyway then why not cut or crop this vegetation and use the available energy while still gaining from the benefits of burning to the environment?

The use of *Calluna* has some advantages relative to other energy crop production. Firstly, *Calluna* grows naturally in a number of locations across the UK and thus does not have to be planted such as is the case for SRC or *Miscanthus* do wherever they are used. Second, it does not require artificial fertilisers or pesticides both of which are commonly used on other energy crops. Third, the removal of *Calluna* vegetation, all be it by burning, brings co-benefits and is presently used to enhance the productivity of an area. Similarly the removal of *Calluna* is a well-established management in these areas and so already has a high degree of societal acceptance and *Calluna* moorland has an established cultural value. Fourthly, there is little other productive use of *Calluna* ecosystems especially in comparison to the lowland settings that would have to be converted to the production of biomass from *Miscanthus* or SRC.

Managed burning of *Calluna*, especially, on peaty or organic rich soils has been shown to have detrimental effects. The managed burning of peat soils have been shown to lead to increased peat erosion [9]. Burning in other settings has been associated with the development of water repellency that limits infiltration [10] which can in turn increase runoff proportion and frequency [11]. Immediately, after burning Worrall and Adamson [12] showed that burning, but not grazing, caused significant changes in soil water composition that were due to changes in the mixing of waters and their interactions, but not causing soil structural change. Of particular concern with respect to water quality has been the impact of managed burning upon water colour and dissolved organic carbon (DOC) as upland peat-covered catchments in the UK are a major water resource and water colour a major limitation in water treatment and some studies (e.g. [13]) have associated observed increases in water colour with increased use of managed burning in the uplands.

Ultimately, a peatland exists because organic matter has preferentially accumulated and managed burning may have some detrimental effects upon this accumulation. Already noted is the potential for increased erosion which is an enhanced loss of particulate organic carbon, and the association between managed burning of peatlands and increased losses of dissolved organic carbon has been noted above. Although one co-benefit of managed burning is to decrease the number of wildfires in the environment it is also true that some managed burning will cause wildfires and so cause sudden losses of carbon to the atmosphere. Indeed any burning, managed or not, represents a release of carbon into the atmosphere. *Calluna* is not a peat-forming species and its presence may restrict the growth of other peat forming species such as sphagnum mosses. It is possible that managed burning may increase opportunities for the development of sphagnum mosses in the short term [7] but keep *Calluna* dominate in the longer term with detrimental effects upon peat and carbon accumulation. Garnett et al. [14] examined peat accumulation under three treatments (grazed/unburnt, grazed/burnt, and ungrazed/unburnt), recalculating the data of [14] based upon all of their data, shows that the mean difference between burnt and unburnt treatments was 2.3 kg m^{-2} (not 2.48 as reported), this gives a mean effect of burning was an additional loss of carbon of 55 tonnes C $km^{-2}yr^{-1}$ (not 73 tonnes C $km^{-2}yr^{-1}$ as reported). However, [14] base their numbers upon peat and not carbon accumulation. Alternatively, [15] examined the contemporary flux of carbon from the same sites and although all plots were shown to be net sources of carbon to the atmosphere the inclusion of burning within the management of a site was to reduce this net source by 39 tonnes C $km^{-2}yr^{-1}$, i.e. managed burning represented an avoided loss of carbon compared to to the losses from *Calluna*-dominated peat ecosystem that is not under burn management. Furthermore, this avoided loss existed even when the loss of biomass during any burn was included.

The discussion above is predicated on the basis that since managed burning of *Calluna* occurs that this management can be swapped for cutting and bailing of *Calluna* as an energy crop with the same or similar impacts. Unfortunately, there is very little literature on the impacts of cutting *Calluna* as opposed to burning and largely this study will have to assume that the impacts, benefits, disbenefits etc known for using burning as a management technique are true for harvesting the *Calluna*. Worrall et al. [16] compared cutting to burning of *Calluna* on a deep peat soil and found that relative to the control and burnt plots, cutting caused greater rises in the water table and decreased the soil water DOC concentrations.

Therefore, this study aimed to answer two questions. Firstly, what is the potential energy available from using *Calluna* as an energy crop? And, what is the greenhouse impact of using *Calluna* as an energy crop?

2. Approach & Methodology

2.1. *Energy value of Calluna*

The energy available from *Calluna* is the balance between the energy available from the harvest minus the energy consumed in its production, harvest and transport. The available energy of the biomass will be:

$$E_{Tot} = Area\ x\ biomass\ x\ harvest\ efficiency\ x\ energy\ content \qquad \text{(i)}$$

Where: Area = the area of *Calluna* that can be harvested each year (ha yr^{-1}); biomass = the biomass of *Calluna* per area (tonnes dry matter $ha^{-1}yr^{-1}$); harvest efficiency (dimensionless); and energy content (GJ tonnes dry $matter^{-1}$). For *Calluna* in the UK it was possible to estimate each of these. This approach was considered relative to two scenarios that only the current area of burning was available for cutting for energy production, and secondly, that all the area of current *Calluna* would be available for energy production.

Area of Calluna – estimates of the area of *Calluna* in the UK were taken from Countryside Survey ([17]-[19]). This number represents the area of heath environment which is not necessarily on peat soils nor in the uplands. The area of upland Britain currently under burn management varies depending upon study. Natural England [20] given as estimate of 16% of all English peatlands are under burn management; Defra [21] give a value of 18% of UK peatlands are currently under burn management; Worrall et al. [22] suggest that 21% of the Peak District

National Park was under burn management; and [23] suggest 40% of English peatlands had been burnt in the 5 years prior to 2000. Therefore, this study takes the range of 16 to 40% which given the area of UK peatlands would mean a range of 2800 to 7000 km^2 currently under burn management, and therefore, dominated by *Calluna*. However, managed burning of *Calluna* takes place on long rotations between 8 and 25 years, with the faster rotation occurring further south where *Calluna* growth rates are that much higher. Therefore, the area of *Calluna* currently burnt each year would between 112 to 875 km^2. The total area of *Calluna* in the UK was taken as 30600 km^2 with between 2700 to 4000 km^2 in England and between 950 and 3000 km^2 in Wales ([17], [18]) and the vaste proportion of the remainder in Scotland. Using the Countryside Survey ([17]-[19]) it was possible to estimate area of *Calluna* in the climatic regions used (Table 1).

Biomass – the maximum amount of biomass present when *Calluna* was burnt and so therefore the amount burnt each year or available to be harvested was taken as equal to the total *Calluna* biomass available on a site. There are several studies of *Calluna* growth rates in British settings (e.g. [24]). However, [6] present a model of biomass production of *Calluna* as part of modelling grazing for sheep. The model of [6] predicts *Calluna* productivity based upon a lapse rate where the lapse rate was adjusted for 10 distinct regions across the country (Figure 1) defined by the mean July temperature, the *Calluna* biomass produced per year (kg dry matter $ha^{=1}$ yr^{-1}) is given by:

$$Biomass = 3462 - 4.41 l_r (A + z_r) \qquad \text{(ii)}$$

Where: A = altitude of site (m above sea level); l_r and z_r = lapse rate constant for region r (Table 1). Equation (ii) means that this study can give regionalised results.

Using this approach it was not necessary to consider the burn frequency. Rather it was assumed that burning occurs as the *Calluna* biomass reaches steady-state and then annual biomass production becomes the annual available fuel and it also then possible to predict required burn frequencies to achieve this. This approach does not mean that cutting of *Calluna* would have to be on plots larger than those typically used within managed burning rather than that area cut each year in each region is weighted by the productivity of that region.

Harvest efficiency – the aboveground biomass present on a site would not be the amount that could be extracted, and indeed nor should be as *Calluna* can regrow from roots more rapidly that it can from seed. Studies of burning of *Calluna* have in effect estimated this efficiency by measuring the loss of biomass over a managed burn, the range of values that have been found are: 75 ± 9% [25]; 88 ± 2% [26]; 66 to 88% [27]; 66 – 92% [28]. Therefore, this study used a value of harvest efficiency of between 66 and 92%.

Energy content – the calorific value of *Calluna* was measured on a Parr 6200 bomb calorimeter. Samples of *Calluna* taken from across the UK were dried to 105^{o}C so as to measure the moisture content and then milled to a sub-mm powder using a Spex 6770 Freezer Mill. A sub-sample of known mass, typically 1g, then had the moisture content raised back to approximately 4% by weight before being combusted in the bomb calorimeter. The 4% moisture does not detract from the calorific value but does aid the combustion process in the bomb and helps prevent sputtering of the sample during the ignition process. The bomb calorimeter was calibrated and standardised on each run of samples using benzoic acid.

The energy costs of *Calluna* harvesting would be relatively simple compared to those for a many other energy crops as there would be no seedling development; no fertilisers to manufacture or apply; likewise no pesticides to manufacture or apply; and furthermore, only one operation would be required per year (harvesting) as there would be no need for ploughing, planting or maintaining the crop. The energy costs were therefore limited to manufacture of the machinery, the harvesting process and the transportation of the harvested product.

Machinery – it was assumed that the harvesting operation was carried out by flail and bailer drawn by tractors. It was assumed that other infra-structure to support the operation was already in place e.g. trackways. For the energy requirement of machinery we used the method of [29] as updated by [30] based upon that assumption that for cutting one tractor with bailer would be required which has a normal working life.

Harvesting process - it was assumed that all the required machinery was kept on the estate office and would not require extra transportation to the site of harvesting. Studies of SRC or *Miscanthus* have tended to assume that all energy crops are grown within 2 km of the machinery base (often a farm – [31]) but for *Calluna,* which grows in more remote upland environments, this would be an underestimate and so we allowed for between 5 and 10 km travel to the harvest area, otherwise energy consumption in harvesting was assumed to be equal to that used in SRC harvesting [30] – this is a conservative assumption relative to other biomass crops.

Transportation – as with the harvesting process the physical locality of much of the *Calluna* means that it would not only be further from the machinery base but the machinery base, e.g. an estate office, will be further from sites of energy production. It was assumed that the site of energy production was between 100-200 km from the farm base. A study such as [32] could assume as little as 30 km travel to the site of energy production. This study assumed that transport over the first 5-10 km was by tractor and by truck over the final 100 to 200 km.

The energy efficiency of energy production from *Calluna* was then judged as the energy yield and energy efficiency:

$$Energy\ efficiency = \frac{Energy_{out}}{Energy_{in}} \quad \text{(iii)}$$

$$Energy\ yield = Energy_{out} - Energy_{in} \quad \text{(iv)}$$

Where: $Energy_{out}$ = the energy obtained from the biomass produced (GJ $ha^{-1}yr^{-1}$); and $Energy_{in}$ = the energy expended in the production and delivery of the biomass (GJ $ha^{-1}yr^{-1}$).

Note that in energy efficiency calculation there was no allowance made for the current activity on the ground. Inherent to our proposition was that *Calluna* could be a low impact energy crop because it was presently under a burning regime anyway, and therefore that was energy presently being lost. Equally, managed burning does require energy expenditure through having machinery present and transport of workers to and from the site, but again it was the energy efficiency of the use of *Calluna* as an energy crop that was being measured. However, when calculating the greenhouse gas benefit of changing from managed burning to cutting of *Calluna* for biomass then the impact of the current activities was important. Second, in the terms of the energy potential of *Calluna* biomass production it was possible to produce values by per hectare for each of the 10 regions defined by [6] and for the UK as a whole based upon average numbers for production and weighted by the area of *Calluna* in each of the 10 regions

2.2. *Greenhouse gas benefit of Calluna energy production*

Unlike energy potential the greenhouse gas impact of *Calluna* cutting has to be judged relative to the other activities that can occur on the same ground. Given the scenarios discussed above then this study needed to understand the greenhouse gas budget of three other land-uses. First, this study considered the impact given that cutting will only replace current burning activity, and so therefore it was needed to estimate the greenhouse flux from managed burning. Secondly, to consider the greenhouse gas budget of cutting of *Calluna* relative to the greenhouse budget of an unburnt and uncut area of *Calluna*. Thirdly, for some areas of some regions *Calluna* there could be a viable greenhouse gas saving alternative to biomass production and that would be reversion to a functioning peat bog. *Calluna* is not a peat-forming species but many of the areas of *Calluna* in the UK are on deep peats, i.e. at some time they were dominated not by *Calluna* but by peat-forming species. Peat formation is generally a GHG sinking process (it is possible that it could be a net carbon sink but due to CH_4 emissions be a net GHG source), therefore, using

Calluna as a biomass crop on a deep peat soil that could be a functioning peat bog represents a GHG saving foregone.

Soil losses – there was only one complete study of the fluxes of carbon to and from a burnt *Calluna*-dominated peatland [15]. Clay et al. [15] measured the carbon budget of unburnt *Calluna*-dominated peatland to be 1560 kgC ha^{-1} yr^{-1} while for burnt *Calluna*-dominated peatland the budget was 1170 kgC $ha^{-1}yr^{-1}$. These budgets refer to the fluxes of carbon between periods of burning and so do not include the loss of biomass at the time of the burning. Equally, these budgets are given in terms of C and so a conversion factor of 3.67 was used to convert them to be in terms of CO_2 equivalents.

To estimate the peat formation sink foregone by the presence of *Calluna* on deep peat the modelling approach of [22] was used. The model of [22] when compared to its driving inputs has been used to derive the following lapse rate for the expected GHG sink (F_{CO2}) of a pristine peat soil without any bare soil:

$$F_{CO2} = 0.52A - 766 \qquad r^2 = 24\%, n = 552 \qquad \text{(v)}$$

Where F_{CO2} = flux to atmosphere of GHG (kg CO_{2eq} $ha^{-1}yr^{-1}$); and A = altitude above sea level (m). All fluxes were judged relative to the atmosphere and so a negative value represents a sink of greenhouse gases from the atmosphere to the terrestrial biosphere. Equation (v) implies that peat soil at sea-level would be a net GHG sink of 766 kg CO_{2eq} ha^{-1} yr^{-1} and that the GHG sink would decline at a rate of 0.52 kg CO_{2eq} ha^{-1} yr^{-1} m of $ascent^{-1}$. Equation (v) was applied across the same altitude range as the *Calluna* production model but could not be applied differently for different regions. This approach also assumed that the *Calluna* was only on deep peat soil. This is a reasonable assumption when considering the scenario of biomass production of *Calluna* replacing the present area under burning management as most of this area would be on deep peat. The assumption will be less effective when considering the scenario of expanding biomass production of *Calluna* in to areas not previously burnt as these are more likely to be on areas of *Calluna* on shallow peat soils. In some regions of the country (e.g. Region 1) it is possible that *Calluna* will be on mineral soils where this approach could well be an overestimate - *Calluna* in region 1 (Table 1, Figure 1) would not be expected to be on peat soils. However, typical approaches to understand the change in soil carbon sequestration (e.g. [33]) work because the biomass crop is replacing other crops on agricultural soils, whereas in this study no crop is being replaced it is a management that is being changed. Assuming that peat is always present is the conservative assumption as greenhouse gas relase would be lower from organo-mineral, or mineral soils

Loss during the burn – this was predicted as per the methods given above for predicting the available biomass available for cutting, i.e. applying the model of [6] it was possible to predict the biomass for each region and altitude. Therefore, the flux of greenhouse gas during the burn (F_{burn}) equals:

$$F_{burn} = 3.67(Biomass\ x\ \%C\ x\ burn\ efficiency) \qquad \text{(vi)}$$

Where: Biomass = the annual *Calluna* production as predicted by equation (ii) (kg dry matter ha^{-1} yr^{-1}); %C = the carbon content of *Calluna*; and burn efficiency = the proportion of biomass lost during the burn. The carbon content of *Calluna* was taken as 50%. The burn efficiency was taken as equal to the harvest efficiency given the above discussion, after all the harvest efficiency was assumed to be equal to the percentage loss of biomass during burns compared to the pre-existing biomass.

Sheep production – it is possible that as a result of expanding the area of *Calluna* that is under management for energy crops to greater than the area currently under managed burning there would bean increase in sheep grazing intensity. Sheep effect the carbon balance of a peat environment through 3 mechanisms. Firstly, through direct emissions, sheep eat vegetation and convert some of that to meat and wool which exported from the environment but they also convert some of that biomass into faeces and urine which is returned to the environment but in a form of carbon more readily turned over and lost to the atmosphere than the plant litter than that which would have formed and contributed to peat formation. Further, some the ingested vegetation is converted to CO_2 and CH_4 through processes of respiration and fermentation, these gases are lost to the atmosphere and CH_4 is a more powerful greenhouse gas than CO_2 [34]. Second, the grazers have an impact on the peat soil through trampling and loss of biomass. Trampling might increase runoff of water and so increase losses of carbon via fluvial pathways, and creation of bare soil and so therefore alter the GHG balance. Thirdly, in the presence of grazers there will be less biomass present on a site than if there had been no grazers and so the potential for litter production and hence peat formation is limited. The direct carbon fluxes from a breeding ewe were based upon the energy budget of a breeding ewe proposed by [35]. The indirect impacts of sheep grazing were predicted using the Durham Carbon Model [22] based on the results for water table change measured by [36] and the resting behaviour observed by [37] for sheep camping and resting. The carrying capacity of each altitude for each of the 10 regions was predicted using the approach of [6], [38] and given 100% *Calluna* cover. The grazing intensity at the carrying capacity was used to estimate the potential additional grazing that could occur with an extension of management of *Calluna* – it was assumed that the vegetation available to the grazers was 100% *Calluna* prior to the extension of cutting management and 33% *Calluna* with 33% sedge and 33% grasses after cutting based upon the observations of [39].

Machinery, harvesting and transportation

The energy conversion rate of diesel was 44 MJ kg^{-1} and the its carbon content was taken as 86%, therefore given the energy consumption predicted above it was possible to estimate the GHG produced from the machinery production, harvesting and required for transportation of the production of *Calluna* for biomass.

2.3. *Energy conversion*

The study used two end-members of energy conversion. In terms of emissions efficiency coal has an energy content of 23 MJ kg^{-1} while natural gas has an energy content of 53.6 Mj kg^{-1}. For coal the emissions factor is 112 g CO_{2eq} MJ^{-1} and for natural gas it is 63 g CO_{2eq} MJ^{-1}. It was assumed that burning *of Calluna* biomass would not be as efficient as that of other more established fuels. For this study it was taken that 1kg dry matter of *Calluna* could substitute for 0.5 kg of coal or natural gas then the greenhouse gas saving due to burning *Calluna* as a substitute for fossil fuels could be made. Again this is a conservative assumption as it could be assumed that a direct substitution on an energy basis were possible.

3. Results

3.1. *Biomass of Calluna*

As predicted by equation (iii) and (iv) the dry production of *Calluna* shows a linear relationship with altitude (Figure 2), but the difference between regions across the UK also being marked. *Calluna* production was predicted to be greatest in the south-east of England (Region 1) where at 300 m asl where production of almost 410 kg dry matter ha^{-1} yr^{-1} was predicted while at the same altitude in the north east of Scotland (region 10) was predicted to have a productivity of only 54 kg dry matter ha^{-1} yr^{-1}. Indeed, it was clear that the approach of [6] and [38] predicts that for many regions *Calluna* will not grow above certain altitudes and for the north east of Scotland (Region 10 – Figure 1) the approach suggests no *Calluna* above 400 m asl.

Given the biomass steady state predicted by [39] it is possible to convert the production graph into an expected burn frequency for each region, if it was assumed that burning occurs at the time when steady-state was just achieved (Figure 3). The results show that while burning as frequent as every 5 years would be possible at low altitudes in region 1, unrealistically long burning rotations are predicted at higher altitudes further north in the UK (eg. Regions 9 and 10 – Figure 3).

3.2. *Energy content*

The energy content of *Calluna* from across the regions of the UK was 18 Mj kg^{-1} which is in line with values reported by [40].

3.3. *Energy production*

The median energy yield per year is shown in Figure 4, the mean average percentage error (MAPE) on these estimates was ±17%. It should be noted that for some regions where it was predicted that *Calluna* would grow (Figure 2) the energy yield was predicted to be negative, i.e. there is no energy return on harvesting *Calluna* in that region at that altitude: this occurs for region 10 in north east Scotland. At maximum production this approach predicts that *Calluna* could provide up to 57 GJ ha^{-1} yr^{-1} with a median value of energy production when weighted by the area of Calluna in each region as 38 GJ ha^{-1} yr^{-1} which is equivalent to 1.7 tonnes of coal ha^{-1} yr^{-1}. The energy efficiency has a median value of 65 ± 19 GJ GJ^{-1}. Whilst the yield of *Calluna* as a biomass crop was at the lower range of yield estimates, though still higher than forest thinnings and straw (Table 2), it has a very high energy efficiency. The low energy yield comes from the low biomass yield per annum, which is in turn the result of the long harvest rotation (up to several decades in the extreme case), however, the high energy efficiency comes from the lack of inputs and lack of additional working required. However, in some regions though the energy yield was on the order of 59 GJ ha^{-1} yr^{-1} and an energy efficiency of 100.

Given the area of managed burning of *Calluna* in the UK it is then possible to estimate that present burning in the UK represents a median energy loss of 821 Pj yr^{-1} with an interquartile range of ± 38%, this is equivalent to 36 ktonnes of coal. However, the total capacity of UK *Calluna* if all of it were cropped within the ranges mentioned then the energy production would have median of 40.7 TJ yr^{-1} equivalent to 1700 ktonnes of coal yr^{-1} – this is 15% of the UK's entire biomass energy target and 67% of UK's target for lingo-cellulose crops and this achieved without taking any land out of production [1].

3.4. *Greenhouse gas emissions*

Given the lower flux of greenhouse gases from burnt as opposed to unburnt sites it was possible that burnt sites would have a lower GHG emissions without even considering cutting for biomass. The GHG emissions of burning were not found to be lower than unburnt sites for burn efficiencies of 92% (the upper value of burn efficiency considered by this study) but it was possible to estimate the burn efficiency at which managed burning would represent an avoided loss of GHG relative to not burning (balance point burning efficiency - Figure 5). The change in the burning efficiency that represent the balance point suggests that for the majority of regions 1 through 4 burning would still represent a loss of GHG relative to the unburnt case. Clay et al. [15] has noted this possibility that the loss during a burn could offset by reduced emissions between times of burning. Here it was predicted that it could occur at range of altitudes for a range of regions. However, it should be noted that this comparison does not include the flux of char involved in each burn. Char is highly refractory carbon and does not cycle into the atmosphere as fast as the plant litter that it replaces and so represents an additional carbon store not accounted for here that might make more areas of burning a net sink of GHG relative to unburnt *Calluna*. Clay and Worrall [26] found 4% of the biomass loss during a burn was converted into char and not into atmospheric gases – at 300m asl in region 1 4% char production in a burn would be equivalent to 396 kg CO_{2eq} ha^{-1} yr^{-1}. Conversely, char production during managed burning would represent a lost energy production. It should be noted that this comparison represents an avoided loss, i.e. both unburnt and burnt *Calluna* both represent sources of GHGs but it is possible that burnt areas lose less than unburnt areas.

Comparing GHG saving for cutting on land that would presently be burnt and substituting it for natural gas used gave a median saving of -9.9 tonnes CO_{2eq} ha^{-1} yr^{-1} with an MAPE of ±19%, the range across altitudes and regions was from -5.8 tonnes CO_{2eq} ha^{-1} yr^{-1} in north east Scotland at 400m asl to -14.4 tonnes CO_{2eq} ha^{-1} yr^{-1} at 350 m asl in Region 1 (Figure 6), but it should be noted that Region 1 is the region least likely to have any Calluna under burn management. The GHG saving from cutting *Calluna* for biomass on land not presently burnt is -7.7 tonnes CO_{2eq} ha^{-1} yr^{-1} with an MAPE of ± 5% and a range of -6.1 to -9.9. The other saving from introducing cutting into previously unburnt *Calluna* was not only due to substitution of current releases from burning but also due to expected increase in sheep grazing possible when increased clearance of *Calluna* was considered.

When comparing to substitution for coal a median saving of -11.0 tonnes CO_{2eq} ha^{-1} yr^{-1} with an MAPE of ±30% was estimated, the range across altitudes and regions was from -5.8 tonnes CO_{2eq} ha^{-1} yr^{-1} in north east Scotland at 400m asl to -17.6 tonnes CO_{2eq} ha^{-1} yr^{-1} at 350 m asl in south west England (Figure 7). The GHG saving from cutting *Calluna* for biomass on land not presently burnt is -8.7 tonnes CO_{2eq} ha^{-1} yr^{-1} with an MAPE of ± 20% and a range of -6.1 to -12.3.

When considering the case of *Calluna* production upon areas which could be functioning peat bog then the picture was considerably different. For the case of substituting for natural gas on ground that is presently burnt the net GHG sink would be -8.2 tonnes CO_{2eq} ha^{-1} yr^{-1} with an MAPE of ±19%. When it is substitution for coal then the net sink improves to -9.2 tonnes CO_{2eq} ha^{-1} yr^{-1} with an MAPE of ±30%. But in comparison to ground that had not previously been burnt and that could be functioning peat bog the median GHG sink was only -0.4 tonnes CO_{2eq} ha^{-1} yr^{-1} with an MAPE of ±41%, and for coal substitution -1.4 tonnes CO_{2eq} ha^{-1} yr^{-1} with an

MAPE of ±96%. As the small magnitude and larger error on these latter values implies that for many altitudes and regions the production of *Calluna* as a biomass crop would no longer represent a net GHG sink on deep peat which could be a functioning peat bog. The predicted GHG saving from *Calluna* harvesting compares favourably with those estimated for *Miscanthus* and SRC ([33], [41] – Table 2).

Given the area of burning and distribution of *Calluna* in the UK it is then possible to estimate that present burning in the UK represents a median GHG saving of 321 ktonnes CO_{2eq} yr^{-1} with an interquartile range of ±39%, but when substituted for coal rather than natural gas then this would be 338 ktonnes CO_{2eq} yr^{-1}. However, the total capacity of UK *Calluna* if all of it were cropped within the ranges mentioned then the GHG saving when substituting for natural gas would have median of 1844 ktonnes CO_{2eq} yr^{-1} within an IQR of ±38%, when the substitution is for coal this increases to 2061 ktonnes CO_{2eq} yr^{-1} within an IQR of ±40%. However, the area of *Calluna* that is on peat soils capable of being functioning peat bog and that has not previously been under burn management is not known.

4. Discussion

This study has shown that because *Calluna* is presently grown and managed but not utilised for its energy value it represents a highly efficient biomass crop. The study has been deliberately conservative in a number of ways. Firstly, it is likely that the most productive sites, i.e. those at low altitude are also likely to be the ones nearest the site of machinery and potentially nearest the sites of energy production, i.e. the energy yield and efficiency and yield of these sites would be greater than predicted here. Secondly, we have assumed that sheep grazing will occur at the carrying capacity of the site and that if cutting was introduced than grazing intensity would increase, again this is the conservative assumption taken to maximise the GHG disbenefits of cutting *Calluna*.

This study does not represent an environmental impact assessment of biomass production from *Calluna*; it has limited itself to consideration of energy production and greenhouse gas savings. Studies of the environmental impact of biomass production do exist for the UK and for a range of biomass crops [41]**.** There are perhaps several important considerations with respect to cutting as opposed to burning, or cutting of previously unburnt *Calluna*. Firstly, there has been a heated debate in the literature regarding the water quality impacts of burning of *Calluna* on peat soils. Studies differ in their spatial and temporal scales as well as the particular flow pathways they consider. At the plot scale, [42] and [43] found no significant difference in DOC concentrations in soil waters between burnt and unburnt sites while [35] and [44] showed a significant decrease in DOC concentration in soil water on burnt sites compared to unburnt sites. At a catchment scale burns more than 4 yrs old, or those on soil types other than blanket peat, show no observed effect on water colour (not DOC) in catchment drainage ([12], [44], [45]). In total or partly blanket peat catchments, however, [12], [44] found a significant positive relationship between the area of new burn (typically <4 yrs old) on blanket peat and drainage water colour (not DOC). However, [45] also note increases in DOC concentration in a range of peat-covered, English catchments, including ones where there was burn management, but observed changes were independent of burning and the variation in increase was larger than that observed by [44]. Clay et al. [46] showed in a series of burns over a 9 year period that burning significantly increased water colour over the 4 years after a burn but not subsequent to that, but crucially there was no significant difference due to burning on the DOC concentration over the entire 9 year period, i.e. many of studies above could be reconciled if this difference between water colour and DOC was considered. It is a moot point as to whether a what company would be more concerned with high water colour or high DOC concentration.

Second, the impact of *Calluna* management upon peat soils when *Calluna* is not a peat-forming species. This has been considered within this study by considering the GHG emissions of biomass cropping of *Calluna* compared to a reversion to functioning peat bog and in which case the saving due to the presence burning means that it would still be a risk-free approach to GHG saving on land where *Calluna* is on deep peat there was no present burning. Again this is a conservative assumption and it was assumed that reversion to functioning peat bog would be possible and it would occur at zero grazing. With climate change it is likely that peat bogs in this country will progressively transition from sinks to sources [47] and so the time course of the GHG saving is likely to shift and shift in favour of biomass production from *Calluna*. However, the study does suggest that if *Calluna* is to be considered as a biomass crop then the first choice of areas would be those where *Calluna* is presently under burn management on soils other than on deep peat. Given the area of *Calluna*-dominated land and the area of deep peat in the UK suggests there would be 12000 km^2 of *Calluna* not on peat soils. Furthermore, these soils might be expected to be at lower altitudes and more likely to form a greater proportion of the *Calluna*-dominated land in the warmer regions (eg. Region1).

This study was not an economic analysis of the production of biomass from *Calluna*. Again economic analyses of biomass production in Europe do exist and tend to show that biomass production from *Miscanthus* and SRC is comparable to wood chip costs (e.g. [49]). But the study has shown that the energy loss from the current area of managed burning (821 PJ yr^{-1}) is greater than the current UK government target for ligno-cellulose biomass production [1]. Anderson et al. [50] estimated that SRC willow in Scotland could produce up to 8.8 GW of energy through electricity and combined heat and power, but the present energy loss due to managed burning of *Calluna* is 26 GW.

5. Conclusions

The study has considered the use of *Calluna vulgaris* as a biomass crop and shown that:

i) *Calluna* has the potential to be a high efficiency if low energy yielding biomass crop because it does not requires the same degree of agricultural inputs (eg. fertilisers) that other biomass crops require.

ii) *Calluna* has a median, area-weighted energy production of 38 Gj/ha/yr at a median energy efficiency of 65 ± 19 GJ_{output} GJ_{input}^{-1}.

iii) The median GHG saving for substitution for natural gas was -9.9 tonnes CO_{2eq} ha^{-1} yr^{-1} or -11.0 tonnes CO_{2eq} ha^{-1} yr^{-1} when substitution for coal is considered.

iv) Burning management in the UK represents an annual energy loss of 821 ± PJ yr^{-1}, but if the entire area of *Calluna* in the UK were brought into energy production the energy yield of 40.7 PJ yr^{-1} would be possible.

v) The total GHG saving for biomass production from the area currently under burn management would be -338 ktonnes CO_{2eq} yr^{-1} for coal substitution, but upto 2061 ktonnes CO_{2eq} yr^{-1} when all the potential area of *Calluna* is considered.

However, for areas of previously unburnt *Calluna* where there would be the possibility of reversion to a functioning peat bog then reversion to functioning peat bog and cropping for biomass production would represent the greatest GHG saving.

References

[1] Defra. UK biomass strategy. Defra, London, UK: 2007.

[2] European Commission. Renewable energy road map: renewable energies in the 21st century: building a more sustainable future. Brussels, Belguim: 2007.

[3] Bauen AW, Dunnett AJ, Richter GM, Dailey AG, Aylott M, Casella E, Taylor G, Modelling supply and demand of bioenergy from short rotation coppice and Miscanthus in the UK. Bioresource Technology 2010: 101: 8132-8143.

[4] Reed MS, Bonn A, Slee W, Beharry-Borg N, Birch J, Brown I, Burt TP, Chapman D, Chapman PJ, Clay G, Cornell S, Fraser EDG, Holden J, Hodgson J, Hubacek K, Irvine B, Jin N, Kirkby M, Kunin W, Moore O, Moseley D, Prell C, Quinn C, Redpath S, Reid C, Stagl S, Stringer LC, Termansen M, Thorp S, Towers W, Worrall F. The future of the uplands. Land use policy 2010: 26: s204-s216.

[5] Hobbs RJ, Gimingham CH. Studies on Fire in Scottish Heathland Communities .2. Post-Fire Vegetation Development. Journal of Ecology 1984: 72: 2: 585-610.

[6] Armstrong HM, Gordon IJ, Grant SA, Hutchings NJ, Milne JA, Sibbald AR, A model of the grazing of hill vegetation by sheep in the UK .1. The prediction of vegetation biomass. Journal of Applied Ecology 1997a: 34(1): 166-185.

[7] Harris MPK, Allen K, McAllister HA, Eyre G, Le Duc MG, Marrs R. Factors affecting moorland plant communities and component species in relation to prescribed burning. Journal of Applied Ecology 2011: 48: 1411-1421.

[8] Albertson K, Aylen J, Cavin G, McMorrow J. Forecasting the outbreak of moorland wildfires in the English Peak District. Journal of Environmental Management 2009: 90: 2642-2651.

[9] Mackav AW, Tallis JH. Summit type blanket mire erosion in the Forest of Bowland, Lancashire, UK: predisposing factors and implications for conservation. Biological Conservation 1996: 76: 31-44.

[10] DeBano LF. The role of fire and soil heating on water repellency in wildland environments: a review. Journal of Hydrology 2000: 231-232: 195-206.

[11] Clay GD, Worrall F, Clark E, Fraser EDG. Hydrological response to managed burning and grazing in an upland blanket bog. Journal of Hydrology 2009: 376: 486-495.

[12] Worrall F, Adamson JK. The effect of burning and sheep grazing on soil water composition in a blanket bog: evidence for soil structural changes? Hydrological Processes 2008: 22: 2531-2541.

[13] Yallop AR, Clutterbuck, B. Land management as a factor controlling dissolved organic carbon release from upland peat soils 1: Spatial variation in DOC productivity. The Science of the Total Environment 2009: 407: 12: 3803-3813.

[14] Garnett MH, Ineson P. Stevenson AC. Effects of burning and grazing on carbon sequestration in a Pennine blanket bog, UK. Holocene 2000: 10: 729-736.

[15] Clay GD, Worrall F, Rose R. Carbon budgets of an upland blanket bog managed by prescribed fire. Journal of Geophysical Research - Biogeosciences 2010: 115: G04037.

[16] Worrall F, Rowson JG, Dixon S. Effects of Managed Burning in comparison to vegetation cutting upon dissolved organic carbon concentrations in peat soils. Hydrological Processes 2013: 27:26: 3994-4003..

[17] Bardgett RD, Marsden JH, Howard DC. The extent and condition of heather on moorland in the uplands of England and Wales. Biological Conversation 1995: 71: 2: 155-161.

[18] Thompson DBA, MacDonald AJ, Marsden JH. Upland heather moorland in Great Britain – a review of international importance, vegetation change and some objectives for nature conservation. Biological Conservation 1995: 71: 2: 163-176.

[19] Morton RD, Rowland C, Wood C, Meek L, Marston C, Smith G, Wadsworth R, Simpson IC. Final Report for LCM2007 - the new UK land cover map. Countryside Survey Technical Report No 11/07 NERC/Centre for Ecology & Hydrology 112pp.(CEH Project Number: C03259): 2011.

[20] Natural England. England's Peatlands – Carbon Storage and Greenhouse Gases. Natural England Report NE257: 2010.

[21] Defra. Assembling UK wide date on soil carbon (and greenhouse gas) in the context of land management. Defra project SP0567: 2009.

[22] Worrall F, Evans MG, Bonn A, Reed MS, Chapman D. Holden J. Can carbon offsetting pay for upland ecological restoration? Science of the Total Environment 2009: 408: 26-36.

[23] Yallop A, Thacker J, Clutterbuck B. Mapping extent of burn management in the North Pennines: Review of extent year 2001-2003. English Nature Research Reports No 698, English Nature, Peterborough, UK: 2006.

[24] Chapman SB, Hibble J, Rafarel CR. Net aerial production by Calluna vulgaris on lowland heath in Britain. Journal of Ecology 1975: 63: 233-258.

[25] Worrall F, Clay GD, May R. Biomass losses and controls upon charcoal production from prescribed burning on a UK peatland. Journal of Environmental Management (in review).

[26] Clay GD, Worrall F. Charcoal production in a UK moorland wildfire - how important is it? Journal of Environmental Management 2011: 92; 675-681.

[27] Kayll AJ. Some Characteristics of Heath Fires in North-East Scotland. Journal of Applied Ecology 1968: 3: 1: 29-40.

[28] Legg C, Davies GM, Gray A. Comment on: 'Burning management and carbon sequestration of upland heather moorland in the UK'. Australian Journal of Soil Research 2010: 48(1): 100-103.

[29] Pimental D. Handbook for energy utilisation in agriculture. CRC Boca Raton, USA: 1980.

[30] Borjesson PII. Energy analysis of biomass production and transportation. Biomass and Bioenergy 1999: 11: 4: 305-318.

[31] Lewandowski I, Schmidt U. Nitrogen, energy and land use efficiencies of miscanthus, reed canary grass and triticale as determined by the boundary line approach. Agriculture, Ecosystems and Environment 2006: 112: 335-346.

[32] Tenerelli P, Carver S. Multi-criteria, multi-objective and uncertainty analysis for agro-energy spatial modelling. Applied Geography 2012: 32: 724-736.

[33] Hillier J, Whittaker C, Dailey G, Aylott M, Casella E, Richter GM, Riche A, Murphy R, Taylor G, Smith P. Greenhouse gas emissions from four bioenergy crops in England and Wales: intergrating spatial estimates of yield and soil carbon balance in life cycle analyses. Global Change Biology –Bioenergy 2009: 1: 267-281.

[34] Houghton JT, Meira-Filho LG, Callender BA, Harris N, Kattenberg A, Maskell K, Climate change 1995: the science of climate change. University Press, Cambridge, 1996.

[35] Perkins DF. The distrubution and transfer of energy and nutrients in Agrostis-Festuca grassland ecosystem. In: O.W. Heal and D.F. Perkins (Editors),

Production ecology of British Moors and Montane Grasslands, Ecological Studies no. 27. Springer-Verlag, Berlin, 1978.

[36] Worrall F, Armstrong A, Adamson JK, The effects of burning and sheep-grazing on water table depth and soil water quality in an upland peat. Journal of Hydrology 2007: 339(1-2): 1-14.

[37] Taylor JA, Robinson GG, Hedges DA, Whalley RDB, Camping and faeces distribution by Merino sheep. Applied Animal Behaviour Science 1987: 17(3-4): 273-288.

[38] Armstrong HM, Gordon IJ, Hutchings NJ, Illius AW, Milne JA, Sibbald AR, A model of the grazing of hill vegetation by sheep in the UK .2. The prediction of offtake by sheep. Journal of Applied Ecology 1997b: 34(1): 186-207.

[39] Forrest GI. Structure and production of North Pennine blanket bog vegetation. Journal of Ecology 1971: 59: 453-479.

[40] Little J. Assessment of the use of landscape management arisings as a feedstock for commercial pellet production – feasibility report. Forestry Commission , UK: 2010.

[41] Heller MC, Keoleian GA, Volk TA. Life cycle assessment of a willow bioenergy cropping system. Biomass and Bioenergy 2003: 25: 127-165.

[42] Ward SE, Bardgett RD, McNamara NP, Adamson JK. Ostle NJ. Long-term consequences of grazing and burning on northern peatland carbon dynamics. Ecosystems 2007: 10: 7: 1069-1083.

[43] Clay GD, Worrall F, Fraser EDG. Effects of managed burning upon dissolved organic carbon (DOC) in soil water and runoff water following a managed burn of a UK blanket bog. Journal of Hydrology 2009: 367(1-2): 41-51.

[44] Helliwell R, Britton A, Gibbs S, Fisher J. Potts J. Interactive Effects of N Deposition, Land Management and Weather Patterns on Soil Solution Chemistry in a Scottish Alpine Heath. Ecosystems 2010: 13(5): 696-711.

[44] Yallop AR, White SM. Clutterbuck B. Evidence for a mechanism driving recent observed trends in dissolved organic carbon release from upland peat soils. Aspects of Applied Biology 2008: 85: 127-132,

[45] Chapman P, McDonald A, Tyson R, Palmer S, Mitchell G, Irvine B. Changes in water colour between 1986 and 2006 in the headwaters of the River Nidd, Yorkshire, UK. Biogeochemistry 2010: 101(1-3): 281-294.

[46] Clay GD, Worrall F, Aebischer NJ, Does prescribed burning on peat soils influence DOC concentrations in soil and runoff waters? Results from a 10 year chronosequence. Journal of Hydrology 2012: 448-449: 139-148.

[47] Clark JM, Gallego-Sala AV, Allott TEH, Chapman SJ, Farewell T, Freeman C, House JI, Orr HG, Prentice IC, Smith P. Assessing the vulnerability of blanket peat to climate change using an ensemble of statistical bioclimatic envelope models. Climate Research 2010: 45: 1: 24: 131-U462.

[49] Styles D, Thorne F, Jones MB. Energy crops in Ireland: an economic comparison of willow and Miscanthus production with conventional farming systems. Biomass and Bioenergy 2008: 32: 407-421.

[50] Anderson RS, Towers W, Smith P. Assessing the potential for biomass energy to contribute to Scotland’s renewable energy needs. Biomass and Bionenergy 2005: 29: 73-82.

[51] Atkinson CJ. Establishing perennial grass energy crops in the UK: a review of current propagation options for Miscanthus. Biomass and Bioenergy 2009: 33: 752-759.

[52] Boehmel C, Lewandowski I, Claupein W. Comparing annual and perennial energy cropping systems with different management measures. Agricultural Systems 2008: 96: 224-236.

Fig. 1. Location of the climate regions proposed by [6] based upon average July temperature.

Fig. 2. *Calluna* productivity with changing altitude for the regions defined within the study.

Fig. 3. Time to steady state biomass with altitude and region.

Fig. 4. Energy yield of produced Calluna with changing altitude and region.

Fig. 5. The balance point burn efficiency at which managed burning would represent an avoided loss of greenhouse gases (GHG) compared to not burning. The balance point burning efficiency is compared varying altitude and region.

Fig. 6. The greenhouse gas (GHG) saving with altitude and region when substituted for energy production from natural gas.

Fig. 7. The greenhouse gas (GHG) saving with altitude and region when substituted for energy production from coal.

Table 1. Lapse rate constants (l_r, z_r) for region r (Figure 1) adapted from [6].

Region	l_r	z_r	Area (ha)
1	0.88	-462.87	41603
2	0.90	-361.05	34070
3	0.92	-263.85	84190
4	0.95	-171.27	202940
5	0.97	-83.32	627658
6	1.00	0.00	510709
7	1.03	78.7	470580
8	1.06	152.77	999143
9	1.09	222.22	48974
10	1.13	287.05	40129

Table 2. Energy yield and energy efficiency of a range of common bioenergy crops in comparison to the results from this study for *Calluna vulgaris*. Where numbers in brackets refer to citations.

Crop	Energy yield (GJ ha^{-1} yr^{-1})	Energy efficiency	Source
Calluna	38	63	This study
Wheat	111	6.7	[30]
Rape	89	6.2	[30]
Potatoes	87	3.0	[30]
Sugar beet	163	7.0	[30]
Logging residues	5.2	29	[30]
Straw	35	23	[30]
Miscanthus	279	32	[51], [52]
Willow	243	78	[52]

Table 3. The reported GHG savings for a range of common bioenergy crops in comparison to the results from this study for *Calluna vulgaris*. Where numbers in brackets are citations.

Crop	GHG saving (tonnes CO_2 ha^{-1} yr^{-1})	Source
Calluna	-5.8 to -17.6	This study
Miscanthus	4 to -5	[33]
Willow	-3 to -4	[33], [41]

Fig.1

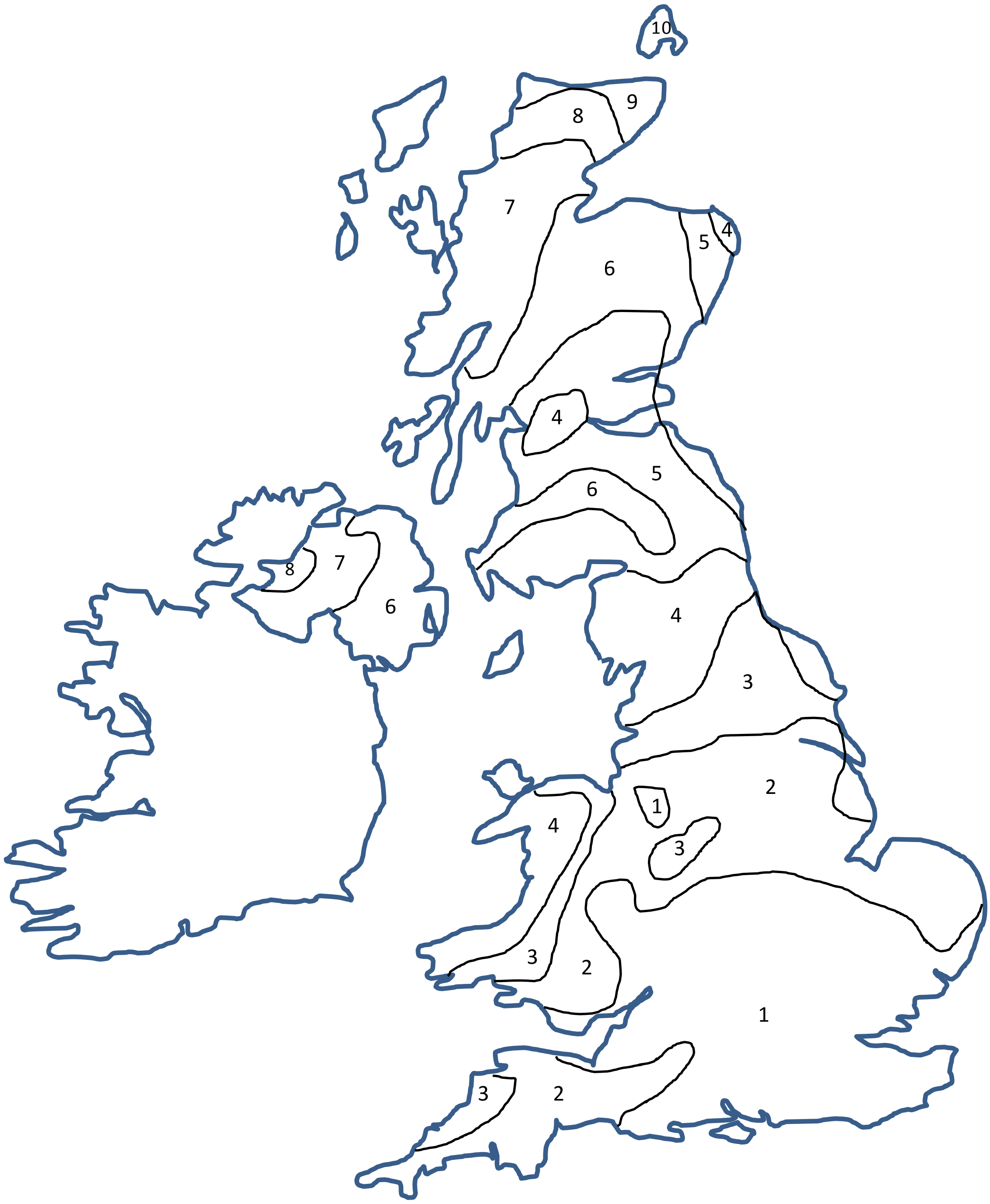
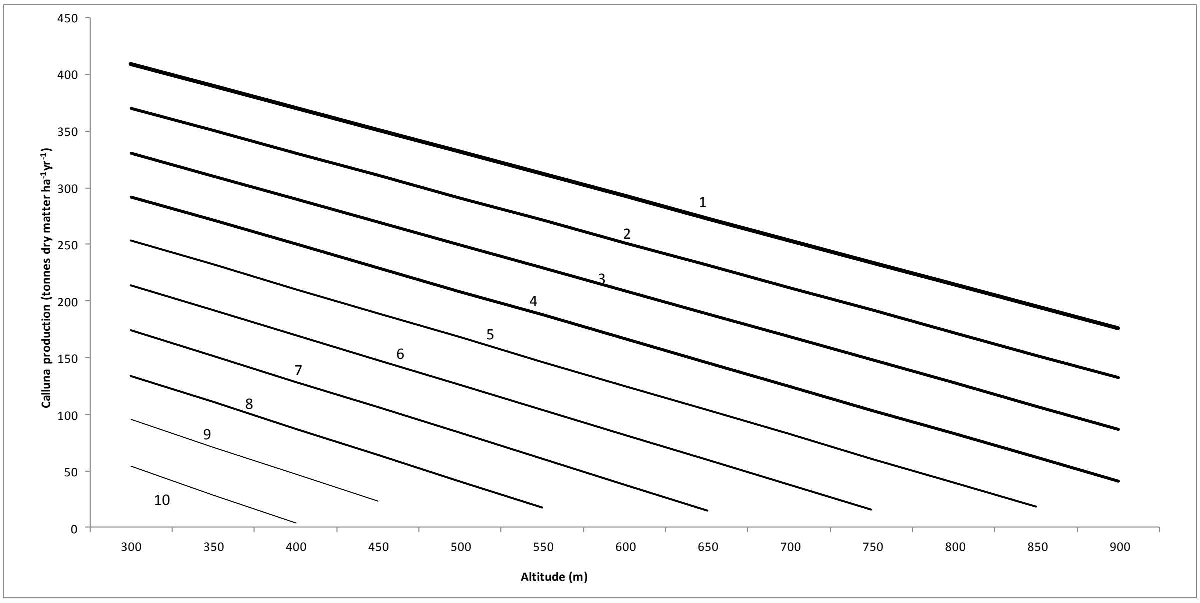
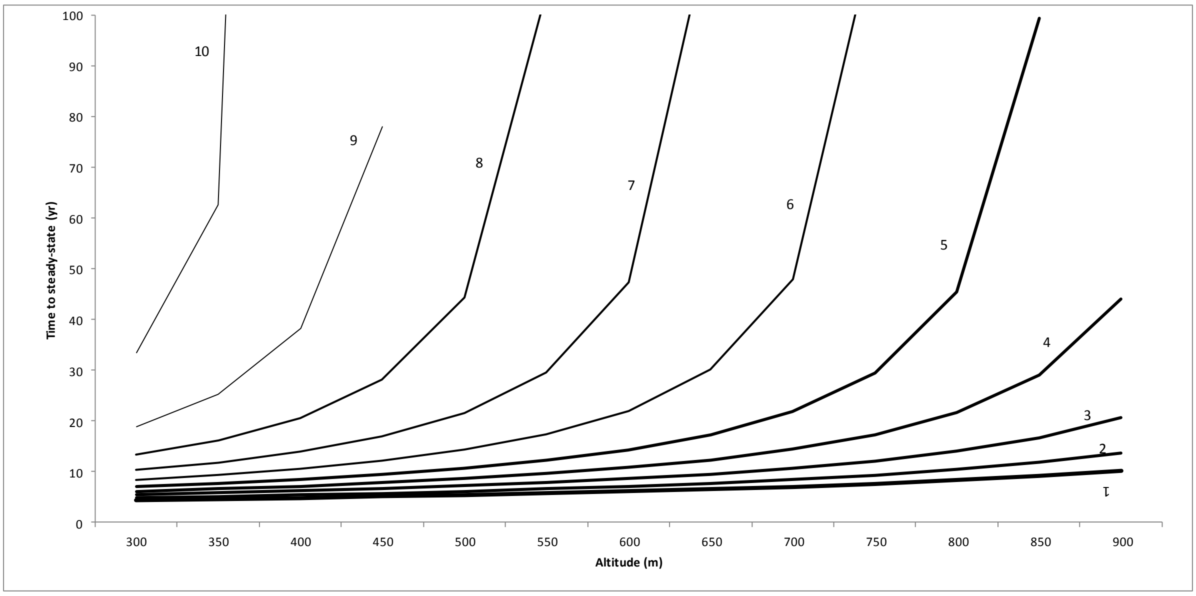


Fig. 2.



Calluna production (tonnes dry matter ha^{-1} yr^{-1})
Altitude (m)
450
400
350
300
250
200
150
100
50
0
300
350
400
450
500
550
600
650
700
750
800
850
900
1
2
3
4
5
6
7
8
9
10

Fig. 3.



Time to steady-state (yr)
Altitude (m)
0
10
20
30
40
50
60
70
80
90
100
300
350
400
450
500
550
600
650
700
750
800
850
900
10
9
8
7
6
5
4
3
2
1

Fig. 4.

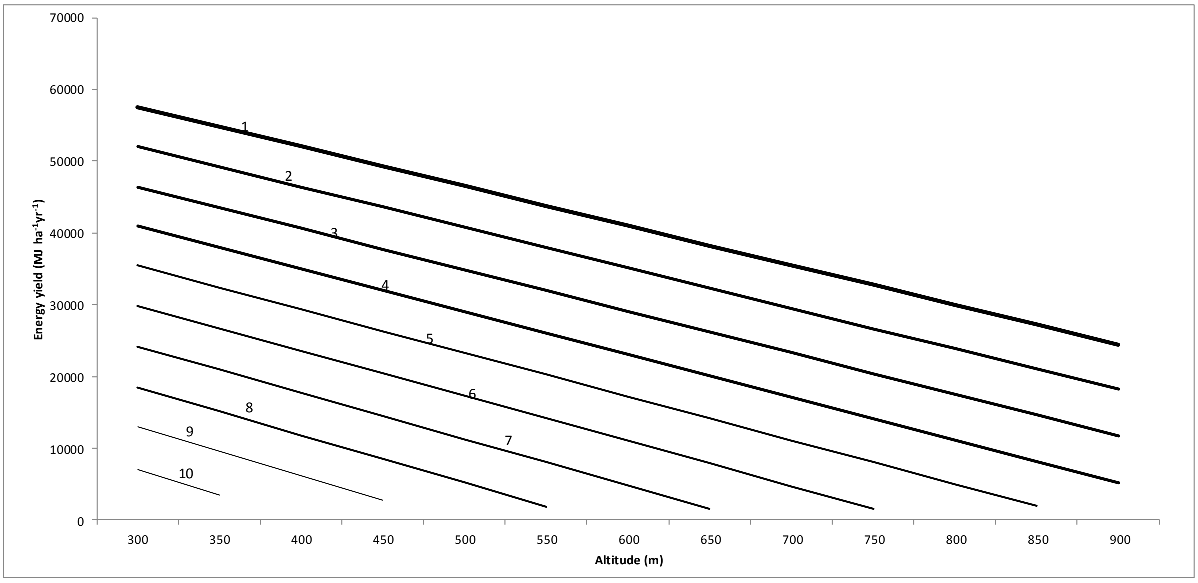

70000
60000
50000
40000
30000
20000
10000
0
Energy yield (MJ ha-1yr-1)
1
2
3
4
5
6
7
8
9
10
300
350
400
450
500
550
600
650
700
750
800
850
900
Altitude (m)

Fig. 5.

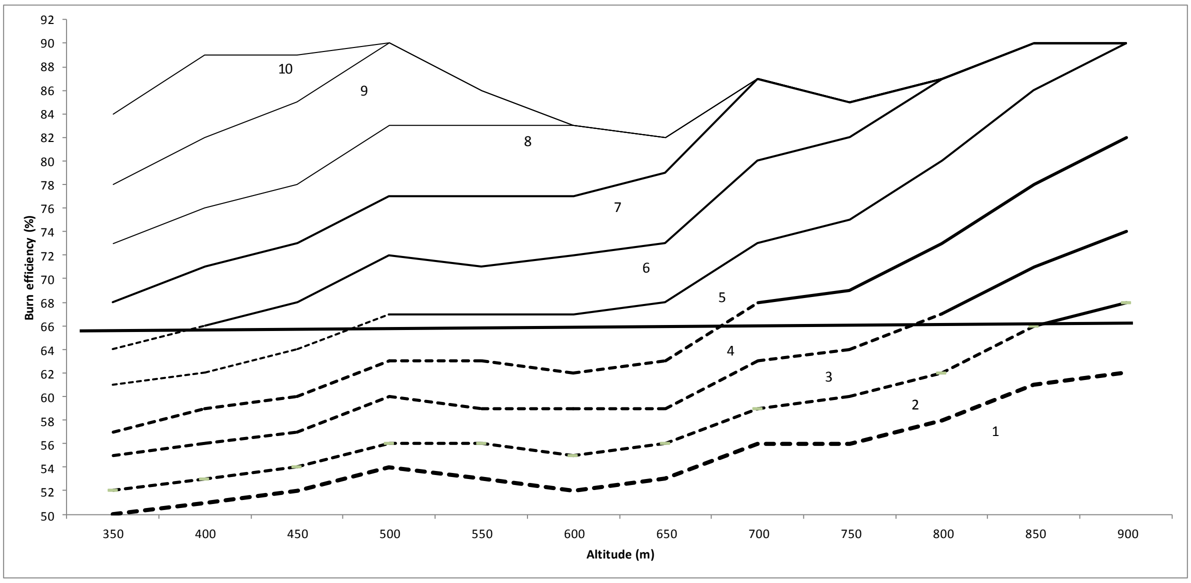

Burn efficiency (%)
Altitude (m)
92
90
88
86
84
82
80
78
76
74
72
70
68
66
64
62
60
58
56
54
52
50
350
400
450
500
550
600
650
700
750
800
850
900
10
9
8
7
6
5
4
3
2
1

Fig. 6.

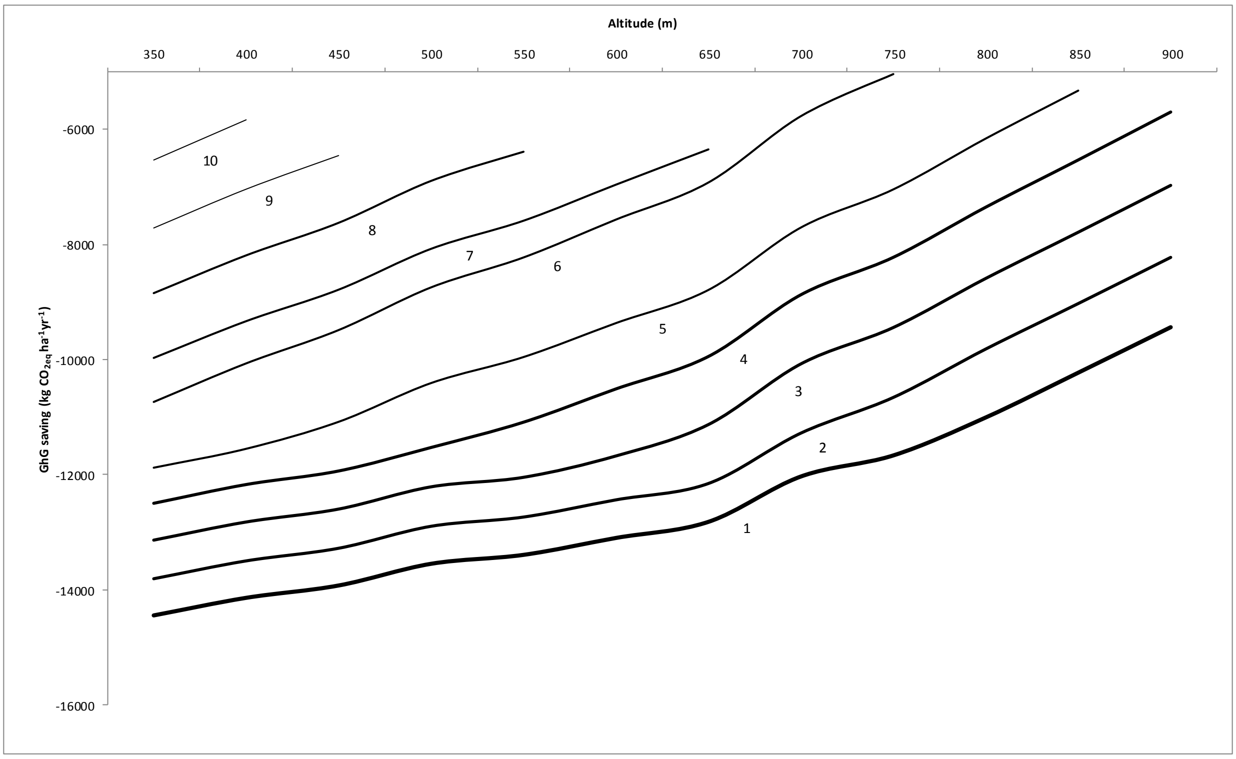
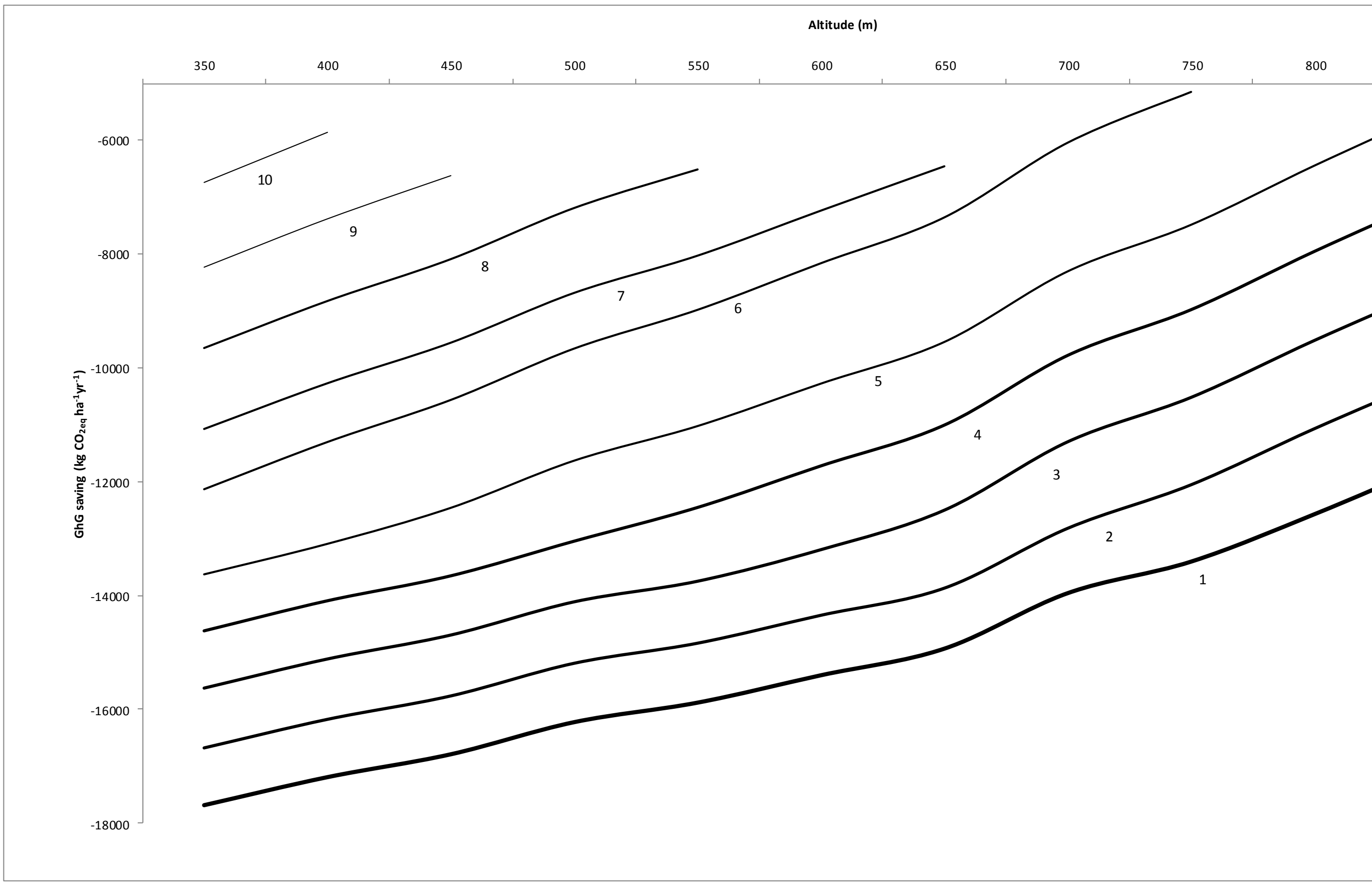

Altitude (m)
350
400
450
500
550
600
650
700
750
800
850
900
GhG saving (kg CO2eq ha-1 yr-1)
-6000
-8000
-10000
-12000
-14000
-16000
10
9
8
7
6
5
4
3
2
1

Fig. 7.


Altitude (m)
350
400
450
500
550
600
650
700
750
800
-6000
-8000
-10000
-12000
-14000
-16000
-18000
GhG saving (kg CO2eq ha-1 yr-1)
10
9
8
7
6
5
4
3
2
1